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ELECTRICAL RESISTIVITY AS MICROSTRUCTURAL PARAMETER FOR THE MODELLING OF SERVICE LIFE OF REINFORCED CONCRETE STRUCTURES

Carmen Andrade (1), Renata d'Andrea (2)

(1) Institute of Construction Science "Eduardo Torroja", CSIC, Madrid, Spain

(2) Spanish Institute of cement and its Applications- Madrid, Spain.

Abstract

There is an increasing interest in developing models for prediction of the service life regarding reinforcement corrosion. In present communication a proposal is made based on the electrical resistivity to calculate both the initiation and propagation periods as well as for predicting concrete aging related to durability and for measuring the efficiency of curing. The model is fundamented in that the Resistivity is a property depending on the concrete porous system and its degree of moisture, and then from its values in saturated conditions, it is possible to find relations between diffusivity and resistivity, then linking concrete microstructure and transport resistance. The relation of resistivity and time is quantified through the square root law, either for chloride penetration as for carbonation. However some additional information is needed due to the reaction of chlorides and carbon dioxide with cement phases: the resistivity has to be factorised by a "reaction factor" accounting for it. Concerning the corrosion propagation period the relation between corrosion and resistivity is provided by an expression previously developed by one of the authors. Aging is introduced by measuring the evolution of the resistivity with time. The paper presents an example of application of the model. Finally it is mentioned that the concrete mix can be designed for a target resistivity and that this parameter can also be used as a performance parameter (Corrosion indicator). Being the measurement of resistivity a non destructive method, it can be as well used for on-site quality control.

1. INTRODUCTION

Design for concrete durability is being the subject of increasing demand due to present prescriptions in codes and standards have shown not to be enough to provide enough durability in aggressive environments and also to the need to optimize the natural resources in order to improve concrete sustainability. Several proposals exist based in modelling the mechanisms of attack [1, 2] or in the so called "performance" concepts or the use of "durability indicators" [3]. Nevertheless, their effective incorporation into the standards seem to be slow and a worldwide controversy exists on which is the best approach, due to the lack of enough tradition and experience of these new proposals.

The service life of reinforcements, t_l, is usually modelled by assuming two periods: the time to initiation of corrosion t_i and its propagation, t_p. Thus, $t_l = t_i + t_p$ [1]. The calculation of the duration of t_l is usually undertaken by considering that the aggressive agents penetrates through concrete cover by diffusion and therefore, Ficks law's is used to calculate a Diffusion Coefficient able to predict the concentration of the aggressive at a certain depth, at several periods of time. Present models of carbonation and chloride penetration [1-3] are usually based on assuming the diffusion as the transport mechanism,. However, these models are composed of parameters, such as the Surface concentration and the diffusion coefficient, whose variation with time, has not been fully quantified, and not having at present enough experience and calibration of these variations, the use of these models to predict the time to reinforcement corrosion is very risky. The practice has shown that different predictions may differ decades [4] which is not an acceptable difference. On the opposite, the resistivity can be monitored with time as it is a non destructive test method which results relatively inexpensive and therefore, its evolution with time may be fully controlled.

In the present paper a proposal is presented based in the use of the electrical resistivity [5-8]. The main advantage is that it is a non destructive measurement and then it can be repeated with a relatively low cos. It can be measured in specimens and in the built structures. The proposal tries to be comprehensive in the sense that it has been developed to be applied to the initiation and to the corrosion propagation periods, being the only model using the same controlling parameter for the whole service life. It also responds to the demand related to the introduction of performance parameters or durability indicators and that being suitable for quality control could also be applicable for modelling for predicting service life. Its basis and use for prediction are presented briefly applied to the corrosion of reinforcement in concrete and some examples are shown on the application of the model.

2. CONCRETE RESISTIVITY

Concrete resistivity is a volumetric property that indicates the ability to the transport of electrical charges through the material. It is quantified through Ohm's law.

$$R = \frac{V}{I} = \rho \frac{l}{A} \tag{1}$$

Where R is the electrical resistance which can be measured applying a voltage and measuring the current I circulating. The ratio between voltage and current is equal to the resistivity multiplied by a "geometric factor" l/A where l= the distance between electrodes and A is the cross section area.

The most common method of measurement is shown in figure 1 (left). Two electrodes as placed in two parallel faces of a concrete specimen or disc and voltage is applied. The other common method is that known as "four points or Wenner method" shown right in the same figure.

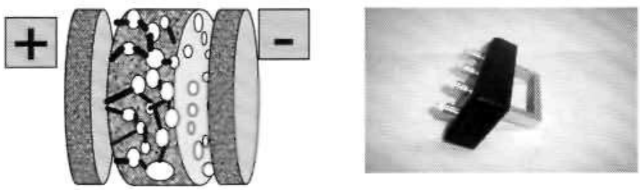

Figure 1 Left: direct ,method to measure resistivity. Left: four points or Wenner method.
Concrete resistivity is an indication of the concrete porosity and and degree of water saturation.

For practical application this method can be used in cylindrical or cube specimens, just before they are tested for mechanical strength. The electrical resistivity of water saturated concrete is an indirect measurement of the concrete pore connectivity [5]. As higher is the porosity, lower is the resistivity due the higher volumetric fraction of pores. On the other hand, while resistivity is related to porosity and connectivity, in non-water saturated concrete, it is as well an indication of its degree of saturation. This relation can be expressed through Archie's law, where ρ_0= the resisitivity of the pore solution, f_v is the volumetric fraction of water and τ is the tortuosity factor, τ:

$$\rho = \rho_0 \cdot W^{-\tau} \qquad (2)$$

Regarding the influence of the chemical composition of pore solution, ρ_0, its impact in the total resistivity is small providing the concrete remains alkaline. At high pH values the pore solution resistivity varies from 30-100 Ωcm, which is comparatively very small taking into account that the concrete resistivity after several days of hardening is in the range of several hundreds Ω·cm. However, when concrete carbonates, then the pore solution is much more diluted and the electrical resistivity of the pore solution may significantly increase and start to be influencing. In chloride contaminated concrete, the chlorides lower the concrete resistivity but not too much, as the resistivity of an alkaline solution is not lowered very much by the presence of chlorides.

With respect to the influence of temperature, it has an important effect on resistivity, which only can be generalized if the ρ values are standarized to a reference temperature that it is proposed to be 25ºC [9]. Other possibility is the use of Arrhenius law, however it has been detected that the Activation energy depends on the degree of saturation and a single value [10] seems not exit. However the final effect of temperature in the corrosion initiation and propagation periods is controversial as an increase in temperature may produce an evaporation, which in turn would effect by slowing both, D and V_{corr}. Therefore, the incorporation of temperature effects on models is very premature and more results are needed. In summary, the electrical resistivity provides indications on the pore connectivity and therefore, on the concrete resistance to penetration of liquid or gas substances, and so resistivity is a parameter which accounts for the main key properties related to reinforcement durability.

2.1 Resistivity and Diffusivity

The ability of resistivity to quantify diffusivity is based in one of the Einstein law which relates the movement of electrical charges to the conductivity of the medium [6][11]:

$$D_e = \frac{k_{Cl}}{\rho_{ef}} = k_{Cl}\,\sigma \tag{3}$$

where D_e= effective diffusion coefficient, k_{Cl} is a factor, which depends on the external ionic concentration, ρ_{ef} = is the "effective" resistivity (in this case of concrete saturated of water) and σ the conductivity (inverse of resistivity). A value of k_{Cl} of 20x10-5 can be used for external chloride concentrations of 0.5 to 1 M. This expression only accounts for the transport of the chloride ions and then, the chloride binding has to be taken into account. This is proposed by means of introducing a new factor, (r_{Cl}= reaction or binding factor). This reaction factor is a "retarder" of the penetration of chlorides. Above equation maintains its mathematical structure but can be now written, where ρ_{ap}, is an "apparent" electrical resistivity in saturated conditions:

$$D_{ap} = \frac{k_{Cl}}{\rho_{ef} \cdot r_{Cl}} \tag{4}$$

Equation (4) can also be applied to the case of carbonation. This is due to carbonation progresses when the concrete is partially dry. That is, as higher is the porosity or the empty pores due to dry conditions, higher the carbonation depth will be. Then the resistivity while informing on the degree of saturation is also informing on the degree of dry conditions. Therefore, equation (3) can be also applied to carbonation providing another constant k_{CO2} is considered for the atmospheric exposure. Then, naming r_{CO2} to the amount of alkaline material able to bind CO_2, it can be written:

$$D_{CO2} = \frac{k_{CO2}}{\rho_{ef} \cdot r_{CO2}} \tag{5}$$

In these equations appear three parameters: the reaction factor, the environmental factor and the aging factor, that have been quantified and the values obtained are presented now.
The reaction factor
With regard to the retarder or reaction factors, $r_{Cl,CO2}$ they depend on the type and amount of cement and therefore, to the extension of reaction of the penetrating substance with cement phases. They can be calculated: a) by direct measurement, b) indirectly by measuring the relation between the effective and apparent diffusion coefficients and c) by calculation from the cement composition. In table 1 are given some r_{Cl} values that were calculated from the multiregime chloride test [12]:

Table 1: Examples of values of the reaction or retarder factor of chlorides, r_{Cl}, for 3 types of cement

Cement	r_{Cl}	Standard deviation
I	1.9	1.3
I+silica fume	1.5	0.5
IIA	3.0	2.1

The factor $k_{Cl,CO2}$ is a factor which depends on the exposure conditions [13]. At present they have been calculated by inverse analysis from tests made in real structures. Those obtained are given in table 2 in function of the exposure classes:

Table 2: Values of environmental factors, $k_{Cl,CO2}$, following the exposure classification of EN206

Exposure class	K_{Cl} ($cm^3\Omega$/año)
X0	200
XC1	1000
XC3	3000
XS1 (d > 500 m distance to the coast line)	5000
XS1 (d < 500 m distance to teh coast line)	10000
XS2	17000
XS3	25000

Aging Factor

As the ρ_{ap} evolves with time, due the progression of hydration an "aging" factor is introduced to account for it. The refinement of the concrete porous systems results in an increase of resistivity with time. If the inverse of resistivity is plotted in function of the time (figure 2) the evolution can be expressed by a function whose power exponent *q*, which is the slope of the straight line, may have different values for OPC than for blended cements[14]:

$$\rho_t = \rho_0\left(\frac{t}{t_0}\right)^q \tag{6}$$

where ρ_t is the value of the resistivity at any age and ρ_0 is the resistivity at the age of the first measurement.

Table 3: Values of the aging factor

Cement	q	Standard deviation
I	0.22	0.01
IIA -P	0.37	0.06
II A-V	0.57	0.08

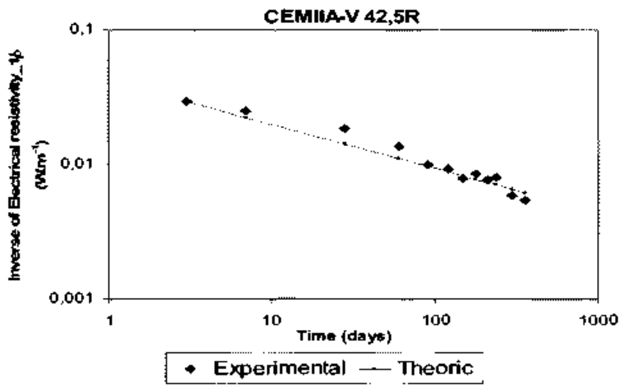

Figure 2 Representation of the inverse of the resistivity with time

3. SERVICE LIFE MODEL BASED ON CONCRETE RESISTIVITY

For the calculation of the **initiation period** the simplest relation between penetration of the aggressive front and time is the so called "square root of time" law:

$$x_i = V_{CO_2,Cl}\sqrt{t} = \sqrt{2D_{ap}t} \tag{7}$$

Where the factor V represents the ease or velocity of penetration of carbonation or chloride front: $V_{Cl,CO2}$ that can be substituted by the square root of the diffusivity, D_{ap} [6]. Now the D_{ap} value can be substituted by resistivity of equation (4) taking into account the aging factor of equation (6). It results the formulation of the initiation period based in the effective resistivity measured in saturated conditions at 28 days:

$$x=\sqrt{\left(\frac{k}{\rho_{ap}}\cdot t\right)}=\sqrt{\left(\frac{k_{Cl,CO2}}{\rho_{ef}\cdot r_{Cl,CO2}}\cdot t\right)}=\sqrt{\frac{k_{Cl,CO_2}}{\rho_{ef}\left(\frac{t}{t_0}\right)^{q}\cdot r_{Cl,CO_2}}\cdot t} \tag{8}$$

For the calculation of the propagation period the model more accepted is (where P_{lim} is the corrosion penetration limit, I_{corr}= is the corrosion rate in μA/cm^2, and V_{corr}= the corrosion rate in mm/year):

$$P_{\lim} = I_{corr} \cdot t = 0.0116 \cdot V_{corr} \cdot t \tag{9}$$

This equation can be expressed in terms of the resistivity by means of the relation (where k_{corr} is a factor whose value is 30 if the I_{corr} is in $\mu A/cm^2$ and the resistivity in k.ohms per cm) where k_{corr} is a constant with a value of $3x10^4 \mu A/cm^2 \cdot k\Omega \cdot cm$:

$$I_{corr} = \frac{K_{corr}}{\rho_{ef}} \tag{10}$$

As was mentioned the resistivity evolves with time and with the amount of moisture that the concrete stores due to the exchange with the ambient and to the local climate exiting in its surroundings[14].

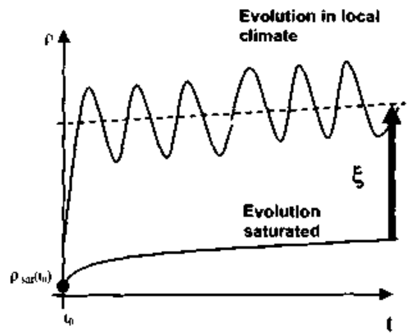

Figure 3 Graphic explanation of the meaning of calculation of ξ as the standardized value of the annually averaged resistivity in a particular climate.

Figure 3 represents the evoultion of the resistivity in a saturated concrete and the imaginary values in a particular climate where the structure is submitted to cycles of wetting and drying. Considering an annual averaged value of the resistivity in that particular climate ρav, for the sake of the modelling, it is calculated a resistivity standarized by its value in saturated conditions which is called ξ:

$$\xi = \frac{\rho_{av}}{\rho_{sat}} \tag{11}$$

Then the expression of the corrosion propagation period can be expressed:

$$t_l = \frac{P_x \cdot \left(\rho_{ef} \left(\frac{t}{t_0} \right)^q \cdot \xi \right)}{K_{corr}} \tag{12}$$

The resulting expression of the service life model using the resistivity for the initiation and the propagation periods is:

$$t_l = \frac{x^2 \cdot \rho_{ef} \left(\frac{t}{t_0} \right)^q}{k_{Cl,CO_2}} \cdot r_{Cl,CO2} + \frac{P_y \cdot \left(\rho_{ef} \cdot \left(\frac{t}{t_0} \right)^q \cdot \xi \right)}{K_{corr}} \tag{13}$$

4.1 Example of application for the initiation period

Assuming a concrete with a cover depth of 5 cm fabricated with a cement type II/A to be placed in an exposure class type XS2: submerged conditions. Considering a service life of 100 years, the values of the reaction, environmental and aging factors, are given in table 4. The calculation end in that the resistivity needed at 28 days age in saturated conditions is of 87,6 Ω m.

Table 4 Input data for a calculation of the concrete resistivity.

Cement type II/A	r_{Cl} = 1,8
Exposure class (XS2)	K (cm^3Ω/year) = 17000 (XS2)
Service life	t (years) = 100
Cover depth	X_{Cl} (cm) = 5
Aging factor during 10 years	q= 0.3

$$5 = \sqrt{\frac{17000}{\rho_0 (\frac{10}{0,0767})^{0,3} \cdot 1,8}} \cdot \sqrt{100} \quad \{ \rho_0(\Omega \cdot cm) = 8760 \rightarrow \boxed{\rho_0(\Omega \cdot m) = 87,6}$$

Resistivity as a Corrosion indicator

Corrosion Indicators are concrete properties that can be used to characterize the performance but without been linked the values to a particular age. That is the use of these Indicators is ranked in classes depending of the nominal service life required, but they are not introduced in models using explicitly the time. Then the Resistivity can be used as a corrosion Indicator if classified in ranges. An example of them is given in Table5. Please notice that it is an illustrative example but that the values have not been calibrated.

Table 5 Example of values of resistivity used as Corrosion Indicator

Period of service life (years)	Values of resistivity at 28 days after curing in saturated conditions (Ωm)
50- 75	70
75-100	90
100-125	120

5. CONCRETE DESIGN FOR A PRESCRIBED RESISTIVITY

A final important advantage of the resistivity when compared to the use of the Diffusion coefficient is that concrete mix can be designed to reach a target Resistivity in a similar manner as is made with respect to the mechanical strength. This is feasible through Archie's law (equation 2 which relates resistivity and porosity) and through Powers expression relating porosity and w/c ratio. It is out of the scope of present work to illustrate the whole procedure but it can be summarized as follows: a) An initial w/c ratio and amount of cement is selected and from them, the porosity of the cement paste is calculated through Powers expression, b) through Archie's law the resistivity is calculated assuming a tortuosity factor. In the calculation of the resistivity all the other factors depending on the aging and the climate in the particular exposure class have to be taken into account.

Although due to the relation of equation (4) would allow to use this methodology for the preparation of concrete mixes for a target Diffusion coefficient, the main advantage of resistivity is the non destructive nature of its test method. The possibility to measure and monitor it in the real structures and in specimens with a relatively inexpensive method, together with its use either for the initiation as for the propagation periods, makes of the resistivity a very promising parameter to assess concrete durability.

6. FINAL COMMENTS AND CONCLUSIONS

The need to provide concrete with target durability has stimulated the development of models to predict service life. These models are based in parameters figuring concrete permeation on resistance to penetration. In general, diffusion coefficient derived from analytical solutions to differential equations as the reproduction of real boundary and initial conditions of the differential equations is not obvious or easy. The method here presented is based in the use of a NDT as resistivity to predict the service life. The use of resistivity is based in Einstein law relating electrical resistance or conductance with the diffusion coefficient. Making certain assumptions this basic law can be applied to the advance of carbonation front or chloride threshold, and to the representation of steel corrosion propagation. The general expression of service life is:

$$t_l = \frac{x^2 \cdot \rho_{ef} \left(\frac{t}{t_0} \right)^q}{k_{Cl,CO_2}} \cdot r_{Cl,CO2} + \frac{P_x \cdot \left(\rho_{ef} \cdot \left(\frac{t}{t_0} \right)^q \cdot \xi \right)}{K_{corr}}$$

This model can be used for calculating cover thicknesses from actual resistivity values or the minimum resistivity for a certain cover thickness. Resistivity can also be used as a performance parameter to be fulfilled by standard specimens at a certain age or as durability and corrosion indicator. Being the measurement of resistivity a non destructive method, it can be as well used for on-site quality control.

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